Hospital Response to Chemical Terrorism: Personal Protective Equipment, Training, and Operations Planning

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Background *Hospitals distant from the immediate site of an incident involving a hazardous materials (HAZMATs) release which could include chemical warfare agents, must develop emergency response plans (ERPs) to protect healthcare professionals if they receive potentially contaminated victims. The ERP must address OSHA, EPA, and JCAHO requirements.*
Methods *The VHA convened groups to develop a hazard and exposure assessment, identify actions for compliance with existing regulatory standards, and review site and operational planning issues. Exposure modeling results were used to derive relationships between operational parameters (time and distance from sites/sources) and potential exposure for healthcare workers.*
Results *According to exposure modeling, level C personal protective equipment is adequate to protect hospital staff distant from the chemical release site. Decontamination runoff and contaminated clothing should also be controlled to limit exposure.*
Conclusions *Development and coordination of ERPs must include the local emergency planning committee, with clear assignment of tasks, locations, and training in order to prevent exposures to healthcare workers.* Am. J. Ind. Med. 46:432–445, 2004. *© 2004 Wiley-Liss, Inc.*

KEY WORDS: personal protective equipment; hospital emergency response plans; chemical warfare agent

Abbreviations: ATSDR, Agency for Toxic Substances and Disease Registry; CERCLA, Comprehensive Environmental Response Compensation and Liability Act; CBRNE, chemical biological, radiological nuclear, and explosive materials; CSEPP, Chemical Stockpile Emergency Preparedness Program; CWA, chemical warfare agent; D2PC, US army personal computer program for chemical hazard prediction; DOD, Department of Defense; EMT, emergency medical technician; EOHSI, Environmental and Occupational Health Sciences Institute; EPA, Environmental Protection Agency; ERP, emergency response plan; HAZMAT, hazardous material; HAZWOPER, hazardous waste operations and emergency response; ICS, incident command system; JCAHO, Joint Commission on Accreditation of Healthcare Organizations; MMRT, metropolitan medical response team; NIOSH, National Institute of Occupational Safety and Health; NIST, National Institute for Standards and Technology; OSHA, Occupational Safety and Health Administration; PAPR, power air-purifying respirator; PPE, personal protective equipment; SBCCOM, US Army Soldier and Biological Chemical Command; SCBA, self contained breathing apparatus; USAF, United States Air Force; VHA, Veterans Health Administration; WMD, weapons of mass destruction.

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INTRODUCTION

Hazardous materials (HAZMATs) incidents have prompted the establishment of Occupational Safety and Health Administration (OSHA) and Environmental Protection Agency (EPA) standards [USEPA, 1989; OSHA, 1995a] as well as standard medical practices for incident response and surveillance of exposed workers [Melius, 1986; Favata and Gochfeld, 1989; Gochfeld and Favata, 1990; Udasin et al., 1991]. Although protocols have been developed for emergency medical response [Bronstein and Currance, 1994], such guidelines are of little use for emergency room personnel as they do not provide any practical instructions on hospital-based procedures. Chemical release incidents are thought to be possible through many different scenarios and present numerous challenges to the facilities responsible for the treatment of victims. The accidental release of harmful materials in transportation events are frequent sources of exposure [Binder, 1989; Hall et al., 1994] and adverse health effects. In addition, chemical incidents related to terrorist acts may involve not only known chemical warfare agents (CWA) [IOM/NRC, 1999], but the opportunistic use of commonly used and transported toxic industrial chemicals [ATSDR, 2001a]. The possibility of such activities forces hospitals to develop emergency response plans (ERPs).

To aid in the development of emergency medical planning, detailed information is available on appropriate responses for both weapons of mass destruction (WMD) [Rogers et al., 1990; Lake et al., 2000; ATSDR, 2002; SBCCOM, 2002; Sidell et al., 2002] and general industrial chemicals [ATSDR, 2001a]. One relevant publication [Bronstein and Currance, 1994] provides personal protective equipment (PPE) level guidance for chemical responses. The Agency for Toxic Substances and Disease Registry (ATSDR) [ATSDR, 2002] recommends a ‘‘high level’’ of PPE, i.e., self-contained breathing apparatus, be used at the scene of the release and in hospital emergency rooms when dealing with contaminated patients (see Table I for details of PPE levels). However, the emergency pocket card from the National Institute for Occupational Safety and Health (NIOSH) [NIOSH, 2003] suggests that a lower level may be used where the exposure levels are known to be acceptable. The promulgation of new emergency planning guidelines by the Joint Committee on Accreditation of Healthcare Organizations (JCAHO) [JCAHO, 2003] emphasizes the need for appropriate hospital action.

In the course of developing ERPs for chemical releases, including terrorist attacks, specific issues have arisen that warrant further attention [Huff, 1991; Kirk et al., 1994; Brennan et al., 1999]. MacIntyre et al. [2000] identified several areas in need of clarification or additional discussion, including victim decontamination, decontamination of wastewater, PPE level, and training. Discussion has focused on the level of PPE needed to protect healthcare workers as they treat contaminated patients [CDC, 1997], including recent recommendations on the use of level B in emergency rooms [ATSDR, 2001a; NIOSH, 2003]. Appropriate training is an issue of particular concern, as some groups have argued that ‘‘contaminated patients’’ trigger the provisions of the Hazardous Waste Operations and Emergency Response Standard (HAZWOPER) [OSHA, 1995a] as promulgated by OSHA. Although the need for hospital-specific guidelines

TABLE I. Description of the Levels of Personal Protective Equipment (PPE) as well as any Inherent Limitations

Level	Elements	Protects against	Usual time required to put on and remove PPE	Maximal period available to work	Constraints
A; B	Fully encapsulating for vapor barriers Self-contained breathing apparatus	All unknown agents	15 min	Two periods of less than 60 min each (approximately 45 min) (“featherweight” bottles, with bottle replacement time needs)	Cardiovascular risk; exercise limitations; physical instability; heat stress Visibility constraints in face shields (fogging; perimeter vision) Glove use (palpation, fine motor manipulation)
C	Negative pressure respirator or powered, air-purifying respirator. Splash-protecting suits	Splash of liquids. Some airborne hazards	1–5 min	8 hr shift with rest breaks for heat illness management (this is actually also a factor in the change schedule for the cartridge and varies by chemical compound)	Heat illness. Glove use (palpation, fine motor manipulation)
D	No respirator				

addressing the issues of decontamination and PPE is recognized, the way in which local area and hospital operational strategies affect the level of PPE has not been scrutinized. Finally, discussions within several hospital systems suggested uncertainty about appropriate medical surveillance and clearance for work.

As a large integrated healthcare system, the Veterans Health Administration (VHA) must provide a certain level of central policy guidance for facilities. The system consists of 142 hospital systems (many with multiple campuses), 800 clinics, and 200 nursing homes around the United States, with approximately 210,000 healthcare workers. To identify and define needed resources, the VHA convened groups to develop a hazard and exposure assessment, identify actions for compliance with OSHA and EPA standards, review site and operational planning issues, and resolve medical testing issues. A detailed description of this process is available [Fedele et al., 2003].

MATERIALS AND METHODS

Hazard Identification

Hazards covered under the current assessment initially incorporated the traditional WMD identified as likely agents in the US Army Chemical Casualty Care Handbook [USAMRICD, 2000]. Documentation such as the Army Field Manual 3–9, *Potential Military Chemical/Biological Agents and Compounds* [US Army, 1990] points out that industrial chemicals that are commonly transported may also be used as weapons. Therefore, situations relevant to several industrial chemicals [Binder, 1989; Hall et al., 1994; ATSDR, 2001b] were also considered in the assessment. These agents represent a broad range of physical characteristics (vapor pressure), toxicology (dermal, systemic, respiratory effects), and exposure routes (dermal, inhalation).

Personal Protective Equipment: Background

HAZWOPER activities require appropriate levels of PPE [Melius, 1986] for defined conditions (see Table I for a summary of equipment properties). However, the equipment is not easily compatible with medical operations [Bronstein and Currance, 1994; Stopford, 2001]. The self-contained breathing apparatus (SCBA) required for levels A and B adds 35–45 lbs to the back, creating physical instability and constraints due to weight and the added cardiovascular load. In warmer climates, heat illness also becomes a very serious concern [Ferguson and Martin, 1985; Beckett et al., 1986; Paull and Rosenthal, 1987; Favata et al., 1990]. In addition, SCBA precludes working for longer than permitted by the content of two containers, according to traditional operations guidance. Given time requirements for changing cylinders, individuals may work, at most, two 45-min periods. The gloves used in levels A and B interfere with manipulation of intravenous solutions and intubation in the absence of frequent drills. Visibility constraints resulting from protective face shields can further compromise the efficiency of medical personnel in level A or B equipment. Level C consists of air purifying respirators, inner and outer gloves, and chemical protective suits. Gloves may be less cumbersome than other constituents of protective equipment but are still not tight enough to support fine-motor manipulation in the absence of frequent practice.

The authors reviewed statutory language and compliance interpretations of pertinent standards from OSHA and EPA in order to identify constraints on planning.

Exposure Modeling and Operations

The authors identified conceptual models and derived equations to estimate source strengths and airborne concentrations of the chemical agent at a location distant from the site of release (see Appendix for modeling details). The possibility of exposure to personnel at a healthcare facility arises as contaminated patients essentially become secondary sources of exposure. Many of the parameters involved in the determination of exposure are probabilistic in character. Therefore, Monte Carlo simulations were performed in order to obtain the estimates of time-integrated exposure concentration. Design Engineering's Crystal Ball 2000 Professional [Werckman et al., 2000], a macro package for Microsoft Excel, was utilized in this effort. The modeling results and planning reconsiderations were then used to derive relationships between operational parameters (time and distance from sites and sources) and potential exposure for healthcare workers. Iterations using assumptions concerning exposure, operational planning, and control strategies identified critical "forcing" elements and produced guidelines for management.

The development of event operations and staging strategies is as important as the selection of PPE in reducing risk to healthcare workers. Potential sources, complicating parameters, and geographical relationships must be considered in the development of plans. For example, decontamination staff downwind of arriving victims may encounter a secondary exposure source due to evaporation of agent from victims' clothing prior to disrobing and showering. Worst-case conditions are used to estimate an upper bound of exposure; if recommended decontamination procedures are followed, this scenario would be highly unlikely.

Medical Programs

The medical program content herein was defined by reviewing the pertinent standards and professional guidelines; considering the levels of protection and decontamination required for effective medical care; and reviewing the scientific literature on appropriate medical surveillance.

RESULTS

Agents of Interest and Concern

Internal discussions and reviews of existing documentation previously described [US Army, 1990; USAMRICD, 2000; ATSDR, 2001b; Stopford, 2001; Fedele et al., 2003] have identified agents of potential concern which encompass a broad range of physical characteristics (such as vapor pressure), toxicology, and exposure routes. Table II presents examples of CWAs with corresponding characteristics; water has been included as a reference. While the list is not all-inclusive, toxic industrial chemicals of interest also generally fall within the range of parameters described in Table II.

Statutory Requirements and Decontamination

Healthcare facilities may encounter two concerns as they plan chemical agent response. First, they must ensure adequate protection of their own employees under OSHA standards. Second, they must consider the effects on the environment under EPA statutes.

The requirement to use an SCBA during emergency response found in HAZWOPER Standard 29 CFR 1910.120(q)(3)(iv) [OSHA, 1995a] applies to employees under the site specific Incident Command System (ICS) who are engaged in emergency response with the intent of handling or controlling the release and may be exposed to a hazardous substance presenting an inhalation hazard. OSHA has not yet determined how 1910.120 will apply to off-site hospitals and healthcare facilities. A review of existing compliance letters and interpretations suggests that all hospitals likely to treat victims of chemical incidents, especially involving WMD agents, must require the use of level B PPE when handling potentially contaminated victims. However, based on the current study, PPE requirements for healthcare workers involved in patient decontamination and triage should be less stringent for several practical reasons. First, the primary source of chemical agent—the terrorist device or transportation accident—will no longer contribute to exposures. This assumption is valid in situations where the medical facility is not the site of incident. This notion further implies that the hospital workers responsible for treating contaminated victims will generally not be ''at the scene.'' Finally, the time elapsed since exposure will have led to a reduction in the level of patient contamination, e.g., due to evaporation (or off-gassing) from the contaminated patient [Westin et al., 1998].

As described in several OSHA standard interpretation and compliance letters, hospital personnel who decontaminate patients should be trained to first responder operations level (OSHA 1910.120(q)(6)(ii)) [OSHA, 1992, 1999]. Healthcare workers' primary activities in such a situation would be clinical care and decontamination. Their inhalation and dermal exposures are likely to be substantially lower than those of the emergency responders actively participating at the site of the chemical release. OSHA is unable to define the contamination levels of patient(s) presented at hospitals post-release, and, therefore, whether level A, B, or C

TABLE II. Summary of the Properties of Chemical Warfare Agents (CWA) and Selected Toxic Industrial Chemicals

Agent symbol	Agent	C_{Vol}(25°C) (mg/m^3)	MW (g/mol)	τ^a (min)	τ^a (hr)	LCt_{50} (mg · min)/m^3	LD_{50} (mg)	LD_{50}/100 g
Cl	Chlorine	25,000,000	71	0.04	0.000667	19,000		
CG	Phosgene	10,000,000	99	0.1	0.001667	3,200		
AC	Hydrogen Cyanide	1,080,000	27	0.925926	0.015432	2,000		
MIC	Methyl isocyanate	≊1,000,000	57.1	≊1	0.016667	2,000–5,000	60–200 mg/kg	
—	Water	22,900	18	43.66812	0.727802			
GB	Sarin	22,000	140	45.45455	0.757576	35	1,700	59
GD	Soman	3,900	182	256.4103	4.273504	35	350	286
HD	Sulfur mustard	920	159	1086.957	18.11594	1,000	1,400	71
GA	Tabun	610	162	1639.344	27.3224	70	1,500	67
GF	GF	581	180	1721.17	28.68617	35	350	286
VX	VX	10	267	100,000	1666.667	15	5	20,000

Properties such as volatility (C_{Vol}) and evaporation time constant (τ) indicate how quickly an agent will evaporate upon dissemination. The relative toxicity of an agent is given by its lethal concentration (vapor) or dose (liquid).

[a]See list of symbols at end of this article for definitions of properties and see appendix for further discussion.

is the most appropriate level of protection [OSHA, 2002b]. OSHA does not explicitly require the use of level B or A [OSHA, 2002a], but compels hospitals to conduct a risk assessment to identify the types and levels of exposures likely in the workplace [OSHA, 2002b]. If personnel are exposed to residual off-gassing from patients rather than to the regional dispersal of a chemical agent, the risk assessment should focus on potential exposures given these specific circumstances.

In addition to the protection of employees under OSHA guidelines, the medical facility must also manage any possible adverse effects on the environment. The EPA issued a Chemical Safety Alert [USEPA, 2000] to address the possibility of environmental degradation from contaminated runoff. Under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) § 107 (d) (1), the ''Good Samaritan'' provision protects emergency responders at the scene of the incident if they pollute through spilling decontamination water in response to imminent hazards. Such ''Good Samaritan'' language may protect emergency responders but does not absolve the need for emergency planning. If a healthcare facility recognizes the risk of such events and plans to receive patients, that facility must contain contaminated runoff (i.e., from decontamination showers and other cleanup efforts).

Site Operations Planning

Tasks for healthcare workers and others include security and crowd-control, decontamination, triage, and treatment in various settings. Clinical treatment guidelines after diagnoses are clear, and tools are widely available. In a true emergency, clinicians are unlikely to refer to textbooks. No clinical algorithms have been published to guide non-clinicians, but specific treatment is needed only for chemical asphyxiants (cyanide) and cholinesterase inhibitors (nerve agents) [ATSDR, 2001c]. VHA assembled these instructions onto a ''chemical agents'' pocket card, in line with the format for its Clinical Practice Guideline support tools [VHA, 2002]. VHA has distributed these to each physician and mid-level provider; the pocket card can also be downloaded from the internet at http://ccl.rutgers.edu/chemcard/.

Even though the clinical treatment guidelines are clear, discussions did reveal confusion regarding planning for decontamination, triage, and treatment at the local level. Despite the availability of literature on the subject [Cox, 1994], clothing removal in general has not been considered to be an essential first step in many settings. This important oversight can lead to unnecessary and preventable exposure to emergency transport personnel due to the presence of the secondary source, e.g., evaporation of a chemical agent from the clothes and skin of a contaminated individual [Torngren et al., 1998]. Additionally, site operations planning must address decontamination runoff and contaminated clothing control as potential sources of secondary exposure [USEPA, 2000]. Since planning for such incidents should be coordinated, the local emergency planning committees (mandated under CERCLA) provide an ideal setting to develop and plan coordinated responses and training that reinforces source control.

Chemical exposure incidents or terrorist events are likely to occur in high-density settings, involving crowds, public transportation, stadiums, etc. Traditional HAZMATs approaches define the site of such a release as a ''hot zone,'' or areas within a defined perimeter around an active release. ''Warm'' zones have lower level contamination and therefore necessitate lower levels of PPE. These conditions differ from those in hospitals, the ''lukewarm'' or ''yellow'' zones, where residual contamination of patients may pose a risk (see Fig. 1 for a schematic identification of these zones). The possibility exists that hospitals will be the direct site of a chemical attack and would therefore become a ''hot'' zone. Clearly, this scenario requires fundamentally different approaches and is not the situation addressed in the present study. Experience suggests that patients may arrive through planned or unplanned routes. In the former case, patients will likely have undergone some form of decontamination, although some of these patients may be incapacitated. In the latter situation, self-referred patients will seek aid wherever they perceive it to be available.

Modeling Results and Operational Impact

The modeling outcomes (see Appendix) suggest several important operational implications. First the major predictors of exposure to healthcare personnel are: (1) the time elapsed since exposure in the ''hot'' zone and (2) the amount of material remaining on the person. For all agents except sarin, doses delivered through airborne routes (i.e., off-gassing) 5 min after leaving the scene should be negligible if clothing was removed at the scene (see Table II). Recognition of an event, identification of transportation means, and transportation to a healthcare facility are not expected to take less than 5 min even under ideal circumstances. Only agents with a vapor pressure similar to water, such as sarin, might still volatilize from the skin and clothing at a sufficiently slow rate to place healthcare workers at risk after relatively short periods of time [Mioduszewski et al., 1998]. Thus, source material needs to be removed from the victim as soon as possible, and the source material must be safely stored in approved HAZMAT containers away from the healthcare workers.

In mass casualty settings, many survivors have appeared in healthcare facilities through non-standard routes, bypassing the planned transportation pathways. It is likely that potentially contaminated patients, whether minimally exposed and healthy, or heavily exposed and acutely ill, will

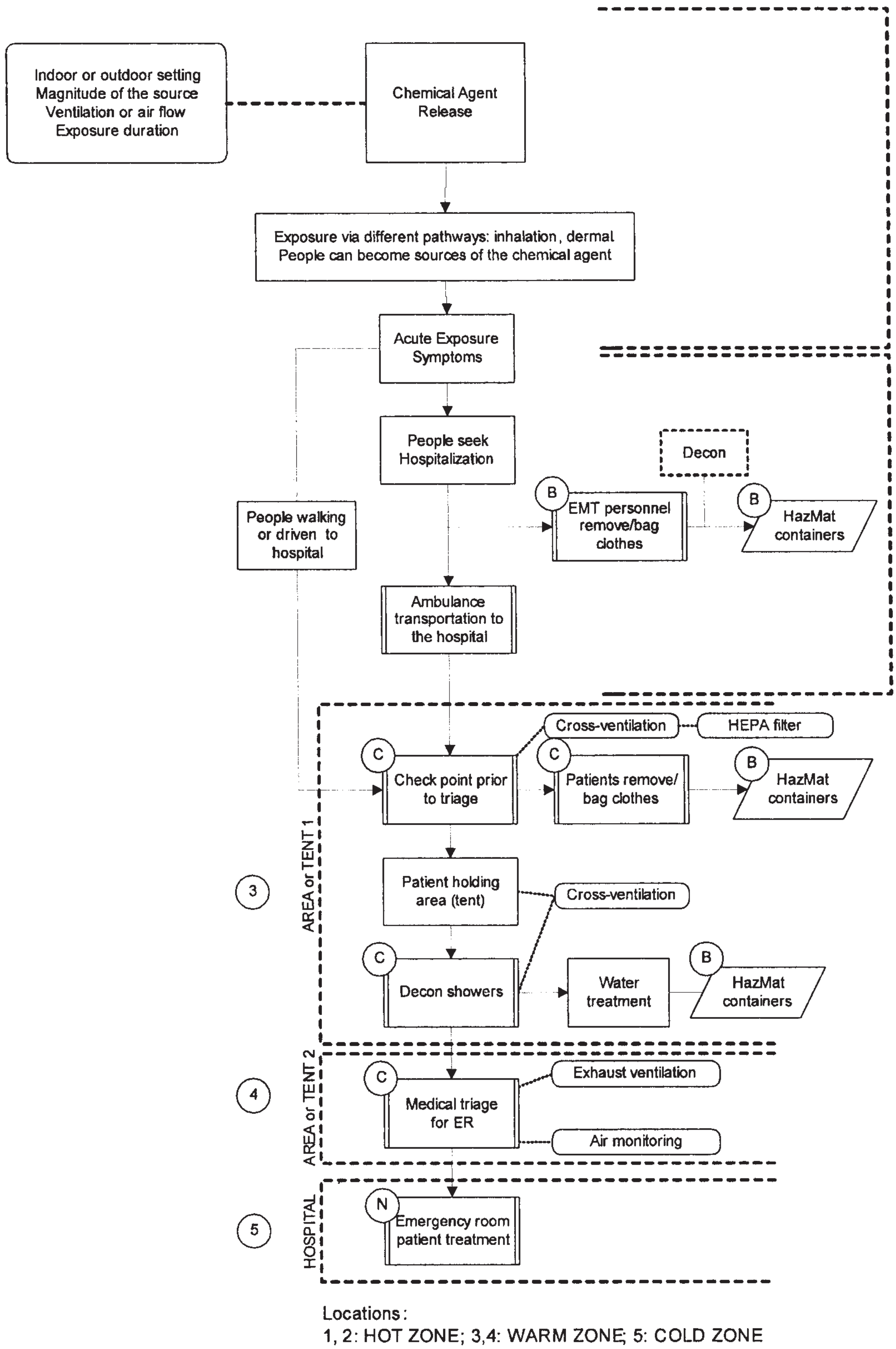

FIGURE 1. Emergency response steps for survivors of chemical attack seeking medical attention at hospital ER. The "hot" zone represents the site of the CWA release, while the "cold" zone is the area with no expected contamination. As the contaminated patients arrive at the ER (i.e. the "warm" zone), they become sources of contamination for the medical personnel. Exposure is limited by use of appropriate PPE.

arrive in healthcare settings without clothing removal. Patients with heavy exposures and chemical loadings that may cause immediate health effects will be severely ill and would likely appear only in small numbers. Conversely, agents with very high characteristic times of evaporation (see Appendix for definition of the time constant τ), or low vapor pressure, may pose a hazard to patients but will not likely pose a threat to healthcare workers.

Second, as clothing is likely to contain a large fraction of the delivered dose, the clothing that remains on the victim, or that is not properly stored, is the next most important predictor of dose. If clothing is removed in the ''hot'' or ''warm'' zone, secondary exposures will be substantially lower. If not, clothing is a secondary source in the decontamination zone, and it requires an explicit exposure control strategy. This requires clothing removal and control immediately upon arrival at the decontamination scene (for example, preparing explicit instructions and planning an efficient delivery system). Some personal items, such as wallets, photographs, plastic glasses frames, etc. may absorb agents in a way that may prevent decontamination and each must be discarded immediately. Valuables, such as wedding rings and precious stones, can likely be decontaminated. Facilities must plan to distinguish between items that can be decontaminated and those that should be discarded. Clothing must be stored in controlled settings away from people during activities. Plastic bags (3 or 6 ml) are likely to provide adequate protection for transport to storage but should not be relied upon for containment of agent. Therefore, a centralized HAZMAT storage container must be available near (but at a safe distance from) the actual decontamination and triage area for all bagged materials. Finally, waste disposal and site clean-up must follow strict hazardous waste operations protocols.

Third, during patient decontamination, both showering and effluent runoff may function as secondary sources of exposure; both require control. EPA mandates planning for runoff control [USEPA, 2003]. Containment is necessary if real contamination is expected. Similarly, if serious contamination is anticipated, ventilation of the decontamination facility is necessary. Where such facilities are permanent hospital infrastructure, extra care must be taken to assure that no cross-contamination occurs in other parts of the facility, through drift from positive pressure, re-entrainment into air intakes, or inadvertent recirculation. Portable units, including tents, have substantial advantages for terrorist events since cross-contamination is less likely. A schematic of the recommended approach to patient receipt, clothing removal, decontamination, and triage is shown in Figure 1.

Understanding exposures requires the use of ''near field'' microscale models rather than regulatory atmospheric dispersion models [OFCM, 1999; Bacon, 2000; Fernando et al., 2001; Kukkonen et al., 2001; Georgopoulos, 2002; ORD, 2002]. There are no existing simple/regulatory models valid to the 1 m scale in a realistic setting, i.e., near buildings, with moving vehicles, people, etc. In fact, understanding the dynamic patterns of sources and resulting concentrations in complex outdoor and indoor microenvironmental settings requires computational fluid dynamics (CFD) techniques that account for local mechanical and convection effects on the transport and deposition of contaminants [Bennett et al., 2000; Hayashi et al., 2002; Winters and Chenoweth, 2002]. Not only do site operations and layout affect exposures, but human movement and posture will also affect contaminant transport patterns. For example, the ''human plume'' resulting from a thermal gradient producing convective turbulence, would likely enhance the release agent and move it along the body at about 50 L/s with a vertical speed of about 0.25 m/s [Settles et al., 1996, 2001] for a standing person.

Several aspects of local site layout can also affect predicted exposures. Orientation of the patient, i.e., lying versus standing, affects concentrations. Upright patients release concentrations along a longer pathway, potentially yielding higher exposures to healthcare workers. The closeness of patients to each other, and up- and/or downdrafts of air will influence exposure. The chaotic nature of emergencies would most likely prevent the control of exposure via proper placement of stretchers and patients.

Medical Surveillance

Workers performing assessment and clean-up operations at hazardous waste sites and emergency response to hazardous substance releases have undergone medical surveillance examinations since several environmental disasters in the early 1980s. The practices used were described in an early document [NIOSH/OSHA/USCG/EPA, 1985] and were initially codified in OSHA's Interim Final HAZWOPER Standard issued in 1986 [Melius, 1986]. (OSHA's final standard, a revision of the Interim Final, was issued in 1989 and became final in 1990.) Practices have evolved since then and have been defined for a program to manage demilitarization of CWAs, namely the Chemical Stockpile Emergency Preparedness Program (CSEPP) [FEMA, 2003]. Medical programs for HAZMATS handling serve two purposes: (a) fitness to work and (b) adverse health effect monitoring [Melius, 1986; Favata and Gochfeld, 1989; Gochfeld and Favata, 1990; Udasin et al., 1991]. OSHA defines requirements under HAZWOPER work (29 CFR 1910.120(q)(9) [OSHA, 1995a]) for emergency responders.

Working in chemical protective suits with powered air-purifying respirators (PAPRs) generates three specific concerns: first, individuals working in chemical protective clothing appear to be at increased risk of heat illness, especially in hot climates. Physical conditioning and acclimatization appear to have few documented benefits [McLellan and Frim, 1994] and are not likely to serve as a useful element to a hospital response program. Second, chronic diseases associated with impaired autonomic sensitivity warrant scrutiny [Beckett et al., 1986]. Third, PAPRs, by themselves, really have no physiological contraindications, as there is no added resistance such as described for negative pressure respirators [Hodous et al., 1986]. However, discomfort from air streams passing the face may be severe enough to prevent effective work. This represents a psychological response that, together with claustrophobia, may preclude participation in a program. The weight of equipment is negligible, so that the cardiovascular concerns that arise with the use of SCBA in levels A or B are insignificant for level C PPE. In general, therefore, neither pulmonary nor cardiac contraindications should preclude wearing level C PPE, but heat illness monitoring programs are necessary. Of course, OSHA's Respiratory Protection Standard requirements for medical evaluation (29 CFR 1910.134 (e)) call for a medical assessment using a defined questionnaire or its equivalent and a follow-up assessment where appropriate [OSHA, 1995b]. Spirometry is not a necessary element of such examinations although there are clearly defined responses and conditions under which it is appropriate.

Equally important is surveillance of health endpoints. Routine screening for pulmonary, dermal, neurological, and gastrointestinal effects represents important baseline documentation. Routine blood testing for such programs generally defines hematologic and hepatic functioning. Body-mass index, as a major contributor to liver test abnormalities, must be recorded. Biological monitoring for the many potential agents is impossible. After the fact, documentation of exposure, particularly for individuals who develop symptoms, should be an integral part of the incident resolution. For many, serial laboratory determinations, such as used for the documentation of cholinesterase inhibition and recovery [Coye et al., 1987] are appropriate.

DISCUSSION

Based upon the current study, level C PPE will protect healthcare workers under the defined conditions and assumptions, i.e., the hospital itself was not the target of the terrorist attack and personnel are performing patient decontamination in the "lukewarm" zone, away from the site of the release. Still, use of level C requires prior planning and protocols at the facility as overexposures are possible. The following constraints must be addressed in planning:

Local: Facility Level

- Staff involved in handling potentially contaminated patients must have a clear understanding of the hazards of agents, broad syndromes associated with exposure, and treatment implications (pocket cards, emergency responders' guides). They must have training in PPE and local plans (HAZWOPER (q)(6)(ii)).
- Medical surveillance must address fitness to work and define baseline medical conditions. Blood and urine should be collected at the end of an incident to define levels of appropriate biological markers of exposure.
- Level C ensembles (chemical protective suits, inner and outer gloves, and PAPRs) are adequate to protect healthcare workers away from the release of agents and after a 10-min lag time.
- The HAZWOPER standard, and JCAHO planning, require a written ERP which should include the decontamination plan, PPE level, and emergency equipment.
- Local ERPs (HAZWOPER (q)(1), (q)(2)) must focus on integrated site layout and operational strategies. A decontamination plan requires site layout that identifies a receiving area before the hospital, that focuses on rapid disrobing and decontamination, and local storage of bagged source material (Fig. 1). Prior to considering the location of staging and holding areas, their relationship to the emergency room/ambulatory care access site, and the intricacies of security and crowd control are essential to the success of decontamination. Clear, fast, and simple instructions broadcast by amplified equipment, to individuals or groups, are essential.
- Facilities must provide fans for air movement across disrobing/holding areas and in decontamination tents.
- Hospital staff in level C ensembles are not adequately protected to handle HAZMAT containers storing clothing and other items, and will not be trained in HAZMAT removal protocols. This work MUST be done by others.
- Bleach decontamination of corpses is likely to allow the deceased to be handled in a normal manner [Blewett et al., 1992].

Local: Area Emergency Planning Committees

It is essential that local committees agree on protocols that require the removal of clothing prior to transport to healthcare facilities. This exposure reduction strategy will benefit emergency medical technicians (EMTs) and ambulance drivers and the receiving healthcare workers. This is the single most important control tactic. All responders must be trained to recognize that prompt removal of contaminated clothing is essential once victims have been removed from the site of ongoing release and before transport to a healthcare facility.

National Level

EMT triage guidance should exist for the clinical presentations used by front-line workers. This is crucial for rapidly acting nerve gases and chemical asphyxiants like cyanide. In general, other agents require decontamination and supportive treatment but victims do not clearly benefit from additional pharmacologically justified treatment. Once detection equipment exists that is sensitive and reliable enough to guide exposure assessment and management, such front-line algorithms may be less important. First responders should distinguish basic syndromes (cholinergic toxidrome, chemical anoxia, mucosal irritants) and relay critical information on likely agents to the receiving healthcare facility.

LIST OF SYMBOLS

C_{Vol}	volatility of chemical agent [mg/m^3].
V_{evap}	evaporation transfer rate [m/min].
m_0	mass per unit area [mg/m^2].
τ	time constant of evaporation process [min].
A_w	area of column of air [m^2].
A_p	surface area of patient contaminated with agent [m^2].
u_W	wind velocity [m/min].
C	vapor concentration downwind of contaminated patient [mg/m^3].
CT	time-integrated exposure concentration [mg-min/m^3].
t_s	start time for integration [min].
LD_{50}	dose lethal to 50% of exposed population [mg].
LCt_{50}	time-integrated concentration lethal to 50% of exposed population after 1 min exposure [mg-min/m^3].

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APPENDIX: Hazard Assessment Modeling

In previous work, a reasonable maximum dose deliverable by terrorist devices was developed by Arnold and Lavonas [2003]. Dissemination was modeled by SBCCOM [Fulco et al., 2000; NIOSH, 2001] to determine the maximum vapor concentration produced by typical devices. In addition, assumptions about battlefield chemical warfare agent (CWA) exposure/dose delivery were reviewed and considered [Fulco et al., 2000]. Agent exposures might occur through aerosol spray or vapor generation [US Army, 1990; Winters and Chenoweth, 2002], although condensation and evaporation may modify the dispersion of the airborne agents. An assumed reasonable upper bound of agent deposition on individuals of 100 g has been suggested if the individual is in the direct line of dissemination. Table II provides the number of lethal doses for cutaneous toxicity [Grotte and Yang, 1998] from 100 g of agent. In general, much lower exposure would be expected as most of the deposited agent will be on clothing [Jenkins et al., 1992]. A practical limit also exists as victims who receive such high levels of lethal doses are not expected to survive. However, to ensure that the vapor hazard levels are reasonable maximum values, the influence of the agent on the individual victim is ignored. For sarin, which has a saturation concentration of over 20,000 mg/m^3 at 25°C, a reasonable vapor concentration is 2,000 mg/m^3 or less than one tenth of saturation [Mioduszewski et al., 1998]. Therefore, the reasonable maximum concentration is not the absolute maximum that is physically possible, but rather a maximum that can be reasonably expected in a terrorist incident.

For the purpose of characterizing potential exposure to healthcare workers, an appropriate time period is assumed for transport to the medical facility. Given experiences in the release of sarin in the Tokyo subway [Ohbu et al., 1997], discussions with emergency medical personnel, and reviews of recent emergency planning for special events (e.g., major sporting events), 10 min appears to be a realistic estimate and was selected as the average transport period.

Evaporation [Topp et al., 1997] is assumed to begin after the conclusion of the dissemination and deposition processes and continues as victims travel to and arrive at the medical facility. Evaporation prior to arrival and decontamination at the facility will limit hazards created by extremely volatile, quickly evaporating materials such as phosgene, chlorine, and hydrogen cyanide [Kukkonen et al., 2001].

Agents will dissipate through both evaporation from free liquid surfaces [Topp et al., 1997] and desorption [Hatch et al., 1987; Karlsson and Huber, 1996; Kukkonen et al., 2001] from porous surfaces of clothing. Fedele et al. [2003] derived characteristic time constants for the evaporation of CWAs. The time constant, τ, is the time for approximately 63% of the current amount of material to leave the surface. In other words, the amount of material on the surface decreases by about 63%, every τ min, until the amount of material becomes negligible [Welty et al., 1984]. This constant is defined in the following manner:

$$\tau = \frac{(m_0)}{C_{Vol} V_{evap}},$$

where m_0 is the amount of mass per unit area, C_{Vol} is the volatility of the liquid, and τ_{evap} is an empirically determined evaporation transfer rate.

Table II illustrates the range of τ values that apply to CWAs and some selected toxic industrial compounds. Compounds that are gaseous at standard conditions, such as phosgene, are expected to evaporate from a liquid state in less than a minute. Water is expected to evaporate completely within hours, sulfur mustard within days, while VX would require years.

Agent that desorbs from a contaminated individual mixes into the passing air and is a secondary source to decontamination personnel standing near the victim. In order to estimate the vapor concentration downwind of the contaminated patient, additional parameters are taken into account. The evaporating agent is assumed to be uniformly mixed within a column of air that has a cross-sectional area (A_w) of about 1 m^2. An area, A_P (also equal to about 1 m^2) of the patient surface is assumed to be contaminated with the reasonable maximum amount of CWA from deposition (100 g). A low wind (or local air flow) speed (u_W) of 1 m/s is assumed. Decontamination begins at a time t_s equal to the average transport period (i.e. 10 min) and continues for 6 hr. The final expression for the time-integrated total exposure concentration [Fedele et al., 2003] is then:

$$\mathrm{CT} = \frac{m_0 A_P}{A_W u_W}\left(e^{-\frac{t_s}{\tau}} - e^{-\frac{t_s+360}{\tau}}\right).$$

The total time-integrated concentration as a function of τ is shown in Figure 2. If τ is very small, the agent evaporates from the skin and clothing before the victim arrives at the medical facility and the potential exposure to medical personnel is limited. If τ is large, a small amount of agent will evaporate during transport to the medical facility. This situation also implies a limited exposure to medical personnel as only a small amount of agent is expected to

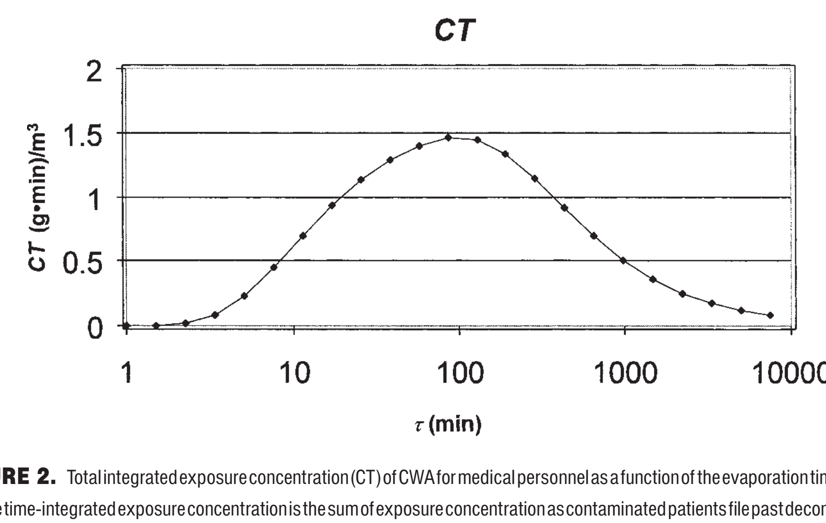

FIGURE 2. Total integrated exposure concentration (CT) of CWA for medical personnel as a function of the evaporation time constant (τ). The time-integrated exposure concentration is the sum of exposure concentration as contaminated patients file past decontamination staff. When τ is small the majority of the agent evaporates prior to arrival at the hospital; for agents with a larger τ, little agent will evaporate not only during transport, but throughout the decontamination process.

volatilize during the decontamination process. Agents with high toxicity and τ values similar to water can be expected to persist at the hospital site and thus would also represent potential hazards. Of the CWAs of concern, sarin, with its combination of toxicity and volatility, poses a realistic hazard after the estimated 10 min transport time. In this analysis of PPE requirements, the focus was on the use of sarin as the worst-case scenario under the assumption that protection against this agent will protect against all others.

In the present modeling analysis, probability distributions were assigned to specific parameters to account for both uncertainty and variability. These simulations were then used to derive distributions of the potential exposure to decontamination staff. Initially, a bivariate Gaussian distribution served to describe the mass deposition on the victim population in a radially symmetric situation, where the greatest potential for contamination exists at the center. The standard deviation (σ) for the final distribution was chosen such that approximately 1 of every 4 or 5 (or 20–25%) victims is contaminated with a significant amount of agent. These probabilities were then used to generate a frequency distribution for mass deposition, as shown in Figure 3. This distribution was fit to a beta distribution which appropriately places the highest probability within the range of lower mass deposition of agent. As an alternative, a triangular distribution was also used to represent mass deposition, with a maximum value of 100 g of agent and a likeliest value of 10 g.

Evaporation, an important removal process, is controlled not only by molecular diffusion, but by macroscopic factors such as local air flows, temperature differences between the contaminated individual and the surrounding air, and proximity of other individuals [Fan, 1995; Bjorn and Nielsen, 1996; Brohus, 1997; Chen and Xu, 1998; Bjorn and Nielsen, 2002; Yokoyama et al., 2002]. These factors will increase the transfer rate of mass. Hence, simulations incorporated variability and uncertainty in transfer values by assigning a probability distribution to the evaporation rate with the value of 0.1 m/min as a lower bound.

Distributions were chosen for other parameters as well. Normal distributions described the exposed surface area of the patient (A_P) with a 1 m^2 mean [USEPA, 1997] and wind (or air flow) velocity (u_W) where the mean is 60 m/min [Karayannis et al., 1997]. The lag time from the initial dissemination of agent to the arrival time of the patient at the medical facility was represented with both a truncated normal and an exponential distribution (with mean value of 10 min) in the simulations [Larson and Odoni, 1981; Zhu et al., 1992; Ayyub and McCuen, 2002].

Other factors in the analysis were held constant. The column of air into which the agent is mixed (A_w) was assumed to be a cross-sectional area of 1 m^2. The volatility of sarin (C_{Vol}) was also held constant. The 6-hr length of the decontamination process is based on the steps in the decontamination procedure and was held at this value as a conservative estimate [Cox, 1994; Hurst, 1997; Brockman, 1998; Raber et al., 2001]. Medical personnel were assumed to be wearing level C PPE, with a respiration protection factor of 1,000 and working for the entire 6 hr duration of the decontamination process.

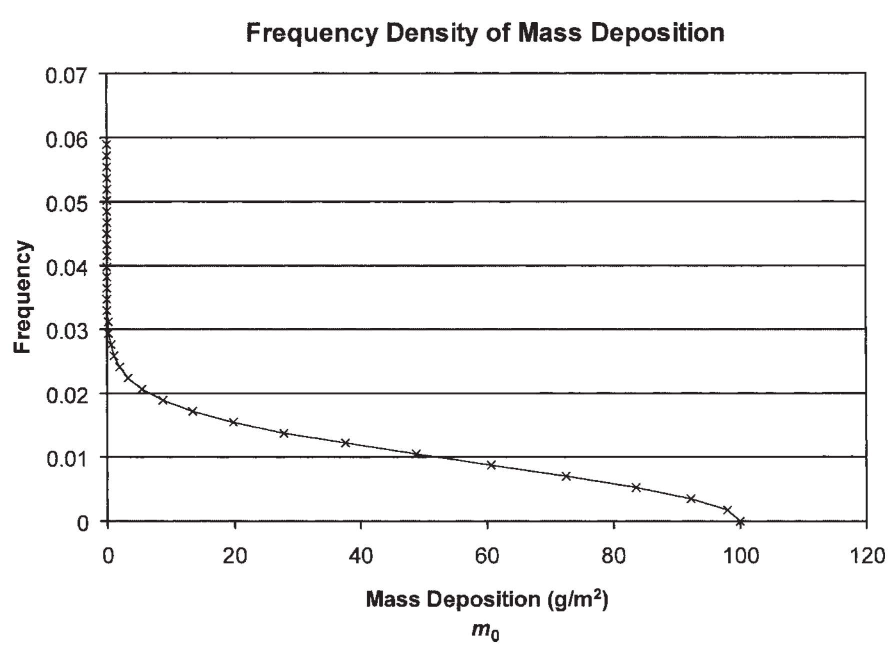

FIGURE 3. Frequency density of initial mass deposition (m_0) of sarin onto victims. This distribution describes the frequency with which victims will be contaminated with a specific amount of sarin. This situation depicts a uniform density of people where the likely mass deposition of the CWA increases as the radial distance increases from the dissemination device.

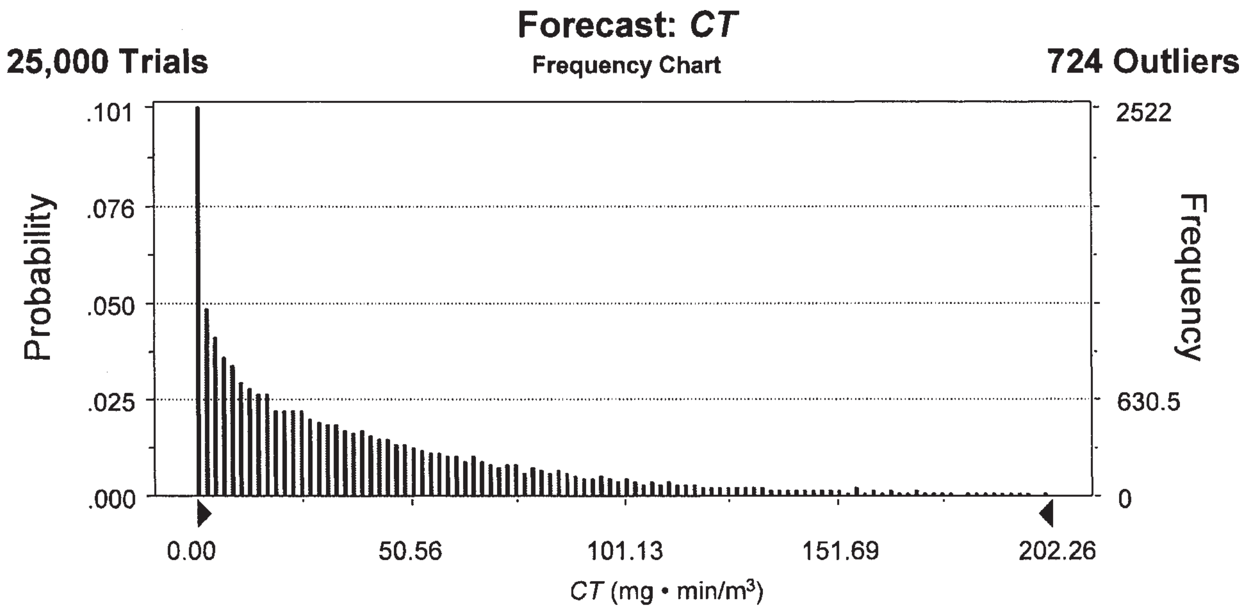

FIGURE 4. Monte Carlo forecast of total integrated exposure concentration (CT) of sarin when a triangular distribution represents the mass deposition (m_0). The time-integrated exposure concentration is the sum of exposure concentration as contaminated patients file past medical personnel. The contaminated body surface area is assumed to be 20%, which represents the potential exposure to healthcare workers when victims immediately disrobe.

A first set of Monte Carlo simulations was performed using the above defined parameters and assumptions with the maximum number of trials set to 25,000. According to the results obtained, in the absence of clothing removal, less than 2% of the trials resulted in a dose in excess of the NIOSH Chemical Biological, Radiological Nuclear, and Explosive Materials (CBRNE) SCBA standard of 2.1 mg-min/m^3 [NIOSH, 2001]. When more realistic distributions for evaporation transfer rate and lag time were incorporated, the percentage above the NIOSH CBRNE SCBA was reduced further.

As previously stated, the majority of the contamination resides on victims' clothing, which leads to the recommended decontamination process that requires disrobing as a first step in order to reduce the exposed surface area. Similar to the prior worst-case scenario, less than 2% of the Monte Carlo trials resulted in an exposure that required the use of an SCBA. When the contaminated clothing is immediately removed upon arrival at the healthcare facility, the level of sarin exposure to a healthcare worker is estimated to be negligible (see Fig. 4).

Even if these exposures are doubled to account for "applied protection factors" or field performance, and to address the standard on "warm zone equipment," no overexposure is expected to occur that would require the use of an SCBA [NPPTL, 2003].